Enhancing Drilling Efficiency Using a New Robust Correlation of Rate of penetration

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ABSTRACT

Rate of penetration (ROP) is the speed of drilling and has a defined drilling unit in most of times that is feet per hours (ft/hr) or meter per hours (m/hr). Rate of penetration (ROP) while drilling is an important factor of drilling efficiency. Drilling operations of hydrocarbon wells are very critical and costly. Each well will be assigned for target days. The only methodology to have an effective well drilling performance is to drill fast and smoothly without affecting drilling operations and rig performance negatively. High and optimized ROP while drilling will help significantly to accelerate well deliveries, have cost and time effectiveness. Drilling brig and bit hydraulics are supportive factors to optimize ROP. There are several factors can affect ROP while drilling and optimize the drilling efficiency. The drilling team must be recognizing the hydraulics influences on well drilling performance and how to contribute for including an effective drilling hydraulics while drilling operation. There several models of ROP, however, most of them are assigned for certain cases such as tri-cone bits or polycrystalline diamond bits (PDC) applications, lack for drilling feasibility and are developed by including limited drilling factors. The objective of this paper is to introduce the first work of a newly developed model that combine mechanical drilling parameters, drilling fluid rheological properties and drilling hydraulics inputs. Drilling hydraulics are critical inputs to have down hole cleaning efficiency in order to optimize ROP. there several drilling hydraulics such as hydraulics horsepower of drilling bits (HHP) and hydraulics horsepower of drilling bit per square inches (H S I). Drill bit pressure loss across bit nozzles and in influences of HHP on annular clearance will be considered to ensure influence of hole cleaning and enhanced ROP. Mechanical drilling parameters, drilling fluid rheological properties and drilling bit hydraulics for similar formation section, and type of drilling fluid were collected and analyzed to determine their effect on ROP.. The developed model confirms determination of important inputs that can be facilitated to improve ROP to assist drilling team. The model was applied in drilling operation in the field and improved drilling efficiency by 50%.

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EXTENDED ABSTRACT

Rate of Penetration (ROP) is defined as the removed rock of drilled formation per unit time. Looking for optimized ROP can reduce drilling time and increase wells delivery. Optimized ROP required a careful consideration for factors of ROP and understanding their impacts. Poor understand of factors of ROP result in well's delivery extension and introduce complicated drilling troubles such as stuck pipe coincident, lost circulation incidents and eventually well control problems if ROP was not monitored and evaluated precisely. There are controllable and uncontrollable factors of ROP as can be seen in table – 1. Controllable factors are those which could be managed for adjusting ROP without influencing drilling operations economically. Uncontrollable factors are very difficult to alter to adjust due to potential hazards like drilling fluid weight, overbalance pressure, type of drilling fluid to and size drilling bits. Three items can be controlled mechanically in drilling drillings which are weight on bit (WOB), drilling strings rotations which can be controlled by top drive found in all drilling contractors' rigs and finally mud pump flow rate that is pumping in the drilled hole to circulate and clean the hole section while drilling. There were published work previously related to ROP models such as Maurer (1962) derived an ROP equation for drilling bits of tricone types. He made a typical assumption that the drilling cuttings are transported from the hole sections.

$$\mathrm{R} = \mathrm{k}\frac{\mathrm{NW}^2}{\mathrm{D}^2\mathrm{S}^2} \quad (1)$$

Where R is drilling rate (ft/hr), k is coefficient of drilling, N is drilling string rotation (rev/min) ,W is applied weight on bit (Klbf), D is hole section size (in) and S is strength of rock formation. Galle and Woods (1963) suggested ROP model with WOB & RPM effect for determining optimum ROP that can ensure long life of bearing and less wear of drilling bit. RPM was related to ROP exponentially and ROP was varied with WOB with k that is dependent on formation rock type.

$$R = Cfd\frac{Crd\,W^k}{a^p}r \quad (2)$$

$$r = e^{-\frac{100}{n^2}}N^{0.75} + 0.5N\left(1 - e^{-\frac{100}{n^2}}\right)\ (Soft\ formation)$$
(3)

$$r = e^{-\frac{100}{n^2}}N^{0.48} + 0.2N\left(1 - e^{-\frac{100}{n^2}}\right)\ (Hard\ formation)$$
(4)

Bingham (1965) did experimental work for proposing a rate of penetration equation. An introduced term which can be found experimentally that is a bit weight exponent (a5).

$$R = K\left(\frac{W}{d_b}\right)^{a5} N \quad (5)$$

where R is rate of penetration (ft/hr), K is coefficient of drilling, N is drilling string rotation (rev/min), W is applied weight on bit (Klbf), db D is hole section size (in) and a5 is bit weight exponent. Bourgoyne and Young (1974) designed a new ROP model mathematically. The mechanical drilling parameters (xn) and the exponents (an) are constant developed by multiple regressions. The model is important because it does not ask for relationships among mechanical drilling parameters and ROP

$$\frac{d}{dt}(R) = e^{\left(a_1+\sum_{i=2}^{8} a_i x_i\right)} \quad (6)$$

Where:

$$x_1 = 1.0$$

$$x_2 = 10{,}000 - TVD$$

$$x_3 = TVD^{0.69}\left(g_p - 9.0\right)$$

$$x_4 = TVD\left(g_p - \rho_{ec}\right)$$

$$x_5 = \ln\left\{\frac{\frac{WOB}{d_b} - \left(\frac{WOB}{d_b}\right)_t}{4.0 - \left(\frac{WOB}{d_b}\right)_t}\right\}$$

$$x_6 = \ln\frac{N}{100}$$

$$x_7 = -h$$

$$x_8 = \ln\left\{\frac{\rho_m}{350\mu d_n}\right\}$$

where; R is rate of penetration (ft/hr), N is drilling string rotation (rev/min), WOB is applied weight on bit (Klbf), h is drilling bit tooth grading dullness, ρm is mud density (lb/gal) , ρec is equivalent circulating mud density (lb/gal), gp is equivalent mud weight (lb/gal), TVD is true vertical depth (ft), µ is plastic viscosity (cP), and dn is the diameter of jetting bit nozzle (in). Warren (1987) proposed an unique ROP model for bit in soft formation with assuming perfect hole cleaning effciecny and cuttings transport does not affect ROP. It was contained the relationship between rock and bit and the influences of wear of drilling bit, pressure of chip hold and cuttings transport and ccumulation.

$$R = \left[\frac{aS^2 d_b^2}{N^b W^2} + \frac{c}{Nd_b}\right]^{-1} \quad (7)$$

where; R is rate of penetration (ft/hr), a,b,c are constants of drilling bit constants, N is drilling string rotation (rev/min), W is applied weight on bit (Klbf), db is hole size diameter (in), and S is strength of rock formation. Hareland et al. (2010) found ROP model for tri-cone bits by performing experimental study for fractured rock and the drilling bit was with single tricone design. The model was applied on real tricone inserts on real fractured rock which indicate the actual drilling scenario application.

$$R = K\frac{80 n_t m RPM^a}{d_b^2 \tan^2\omega}\left(\frac{WOB}{100 n_t \sigma_p}\right)^2 \quad (8)$$

where; R is rate of penetration (ft/hr), K is a coefficient drilling, nt is the number of insert, m is the number of inserts that penetrates per revolution, RPM drill string rotation (rev/min), WOB is weight on bit (Klbf), db is size of drilling bit (in), ω is formation angle, a, b are constants and σ is ultimate rock strength (psi). Ahmed AbdulJabbar (2017) developed a new ROP model by including drilling fluid plastic viscosity (PV) with mechanical drilling parameters and formation strength. 16.96 is conversion factor, WOB is weight applied on bit while drilling by top drive and travelling block in (Klbs) , RPM is revolution per minute of drill-string rotation in (Rev/min), T is torque of drilling which is a function of WOB & applied RPM (Klbs-ft), SPP is standpipe pressure which is mud pump pressure while pumping flow rate in (psi), GPM is pumped flow rate of rig mud pump in (Gal/min), d_b is size of drilling bit , MW id mud weight or drilling fluid density in (PPG), PV in (CP) and UCS is ultimate compressive strength of rock formation in (psi).

$$ROP = 16.96\frac{(WOB^b x RPM x T x SPP x GPM)}{dp^2 x\, MW x PV x UCS^b} \quad (9)$$

Mohammed M Al-Rubaii (2019) proposed a newly developed ROP model by combining mechanical drilling parameters, wellbore trajectory dogleg severity and hole cleaning indicators such as cuttings concentration in annulus (CCA) and carrying capacity index (CCI) of drilling cuttings generated in hole section by the implemented ROP while drilling and drilling fluid ability to have capable lifting capacity of cuttings transport. C1 to C8 are coefficient and can be determined by non-linear regression methodology. DLS is dogleg severity that is a function of true vertical and measured depths, inclination and azimuthal angles, the unit of DLS is degrees/100ft. CCA is percentile unit or in digits and CCI is unite less.

$$ROP\left(\frac{ft}{hr}\right) = -C1 * GPM\left(\frac{gal}{\min}\right) + C2 * RPM\left(\frac{rev}{\min}\right) + C3 * TRQ(lb - ft) + C4 * WOB(lb) + C5 * DLS\left(\frac{deg}{100ft}\right) - C6 * MW(PCF) + C7 * CCA + C8 * CCI + C9 \quad (10)$$

Mohammed M Al-Rubaii (2019) suggested a new model for ROP that was characterized by mechanical drilling parameters for typical and complete set of data. The constants were found using non-linear regression by Matlab codes were developed. The empirical correlation for ROP as follows:

$$ROP = f1 + f2 + f3 + f4 \quad (11)$$

$$f1 = C1(WOB)^{C2} + C3$$

$$f2 = C4(RPM)^{C5} + C6$$

$$f3 = C7(TRQ)^{C8} + C9$$

$$f3 = C10(Q)^{C11} + C12$$

$$ROP = C1(WOB)^{C2} + C4(RPM)^{C5} + C7(TRQ)^{C8} + C10(Q)^{C11} + C12 \quad (12)$$

Moraveji and Naderi (2016) built an ROP model which combines drilling parameters, such as weight on bit, bit rotational speed, bit jet impact force, yield point to plastic viscosity ratio, and 10 min to 10 s gel strength ratio. The developed model was showing 95% accuracy with measured ROP field data. Xian Shi (2016) used 5000 data points different parameters such as RPM, WOB, SPP, MW, viscosity of drilling fluid, abrasiveness of drilled formation, drill-ability of formation, unconfined compressive strength (UCS), wear of drilling bit, drilling bit type and drilling bit size. 75% of selected data were used for training and 25% for testing. By using artificial neural network (ANN), a coefficient of determination of ($R^2 = 0.91$) was obtained for training and ($R^2 = 0.90$) for testing. Abdulmalek (2018) used support vector machine (SVM) for predicting ROP by using the drilling mechanical parameters and mud properties. 400 data points in shale formation of 10 input parameters were utilized such as, WOB, RPM, GPM, SPP, drilling torque, MW, drilling fluid plastic, drilling fluid march funnel viscosity, drilling fluid yield point and drilling fluid solid content percentage. 70% of the data were used for training process of model development and the rest 30% for testing the ROP model. The relationship accuracy is $R^2 = 0.997$. For developing ROP model one sections in Field A, was selected consists of sandstone formation and limestone formation which is a hard formation and usually drilled using PDC bit with a size of 12.25”. Data were collected from 4 to 6 wells from each section to build digital twin techniques such as building based physical model and feeding the developed model with real-time readings and compare it with actual measured ROP provided by rig sensor during drilling. The data were cleaned, filtered and correlated with ROP to check the critical parameters that can influence ROP while drilling. Mechanical parameters such as (WOB, TORQUE, RPM, GPM, SPP , drilling bit aggressiveness (µ)) , drilling fluid rheological field , surface readings were collected such as (PV, YP, MW and MF) to combine them with mechanical drilling parameters and inputs drilling bit hydraulics such as hydraulics horse power of drilling bit (HHP), total flow area of bit nozzles (TFA), number of nozzles (n), sizes of nozzles (dn), pressure bit loss across nozzles (dpb) and hydraulics horsepower per square inches of drilling bit (H S I) were used to integrate them with mechanical drilling and drilling fluid parameters. The developed ROP model is composed of mechanical drilling parameters, drilling fluid properties and drilling hydraulics parameters. The accuracy was 90 % compared with ROP readings of real-time sensor of measured ROP while drilling. The developed ROP model is as follows:

$$ROP = 0.00012 \frac{RPM\ x\ \mu^{0.85}\ \mathrm{x\ SPP}^{0.85}\ \mathrm{x\ GPM}^{0.01}\ \mathrm{x\ HSI}^{0.001}}{10\left(\frac{\mathrm{PV}}{\mathrm{YP}}\right)^{0.5}\left(\frac{\mathrm{MW}^{0.1}}{\mathrm{MF}^{2}}\right)}$$

(13)

Where,

RPM is drilling string rotation (rev/min), µ is bit aggressiveness, SPP is standpipe pressure (psi), GPM is mud pump flow rate in (gal/min). H S I is hydraulic horsepower per square inches of drilling bit in (hp/in), PV is drilling fluid plastic viscosity (CP), YP is drilling fluid yield point (CP), MW is drilling fluid density in (lb/cubic feet) (PCF) and MF is drilling fluid march funnel viscosity in (sec) or (lb/(100 ft square)). The results are shown in fig.1

Table 1: ROP Factors.

Factors	Classifications
Depth	Uncontrollable
Formation lithology and strength	Uncontrollable
Well trajectory	Uncontrollable
Drilling fluid Type	Uncontrollable
Drilling Fluid density	Uncontrollable
Over-balance and Bottom Hole pressures	Uncontrollable
Size of drilling bit	Uncontrollable
Wear of drilling bit	Uncontrollable
Bit design	Controllable
Drilling Fluid rheological Properties	Controllable
Weight on bit (WOB)	Controllable
Drill sting rotation(RPM)	Controllable

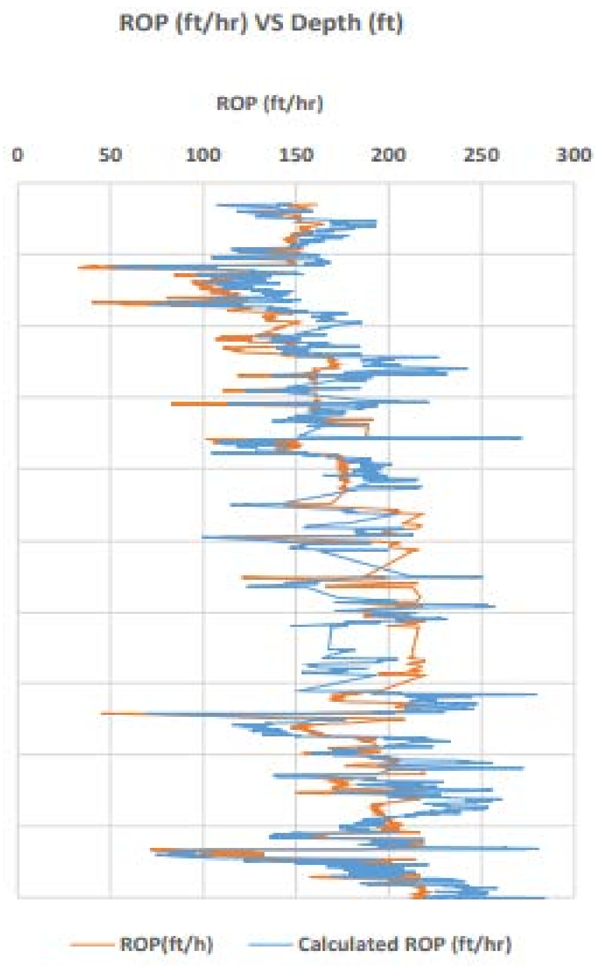
Mud pump flow rate (GPM)	Controllable
Total flow area of bit jetting nozzles (TFA)	Controllable
Mud Motor or Rotary steerable system	Controllable
Bottom hole assembly design	Controllable

Equations

- $R = k\frac{NW^2}{D^2S^2}$
- $R = Cfd\frac{Crd\,W^k}{a^p}r$
- $R = K\left(\frac{W}{d_b}\right)^{a5}N$
- $\frac{d}{dt}(R) = e^{\left(a_1+\sum_{i=2}^{8} a_i x_i\right)}$
- $R = \left[\frac{aS^2d_b^2}{N^bW^2} + \frac{c}{Nd_b}\right]^{-1}$
- $R = K\frac{80n_t mRPM^a}{d_b^2\tan^2\omega}\left(\frac{WOB}{100n_t\sigma_p}\right)^2$
- $ROP = 16.96\frac{(WOB^b xRPMxTxSPPxGPM)}{dp^2x\,MWxPVxUCS^b}$
- $ROP\left(\frac{ft}{hr}\right) = -C1*GPM\left(\frac{gal}{\min}\right) + C2*RPM\left(\frac{rev}{\min}\right) + C3*TRQ(lb-ft) + C4*$

  $WOB(lb) + C5*DLS\left(\frac{deg}{100ft}\right) - C6*MW(PCF) + C7*CCA + C8*CCI + C9$
- $ROP = C1(WOB)^{C2} + C4(RPM)^{C5} + C7(TRQ)^{C8} + C10(Q)^{C11} + C12$
- $ROP = 0.00012\frac{RPM\;x\;\mu^{0.85}\;x\;SPP^{0.85}\;x\;GPM^{0.01}\;x\;HSI^{0.001}}{10\left(\frac{PV}{YP}\right)^{0.5}\left(\frac{MW^{0.1}}{MF^2}\right)}$

- $TFA = \frac{3.14}{4}\left(n1\left(\frac{d1}{32}\right)^2 + \cdots + ni\left(\frac{di}{32}\right)^2\right)$, n is number of bit nozzles, d1 and di are nozzles sizes
- $HHP = \frac{(dpb)GPM}{1714}, dpb = \frac{MW\ GPM^2}{81000\ TFA^2}$
- $HSI = \frac{1.27\ HHP}{db^2}$



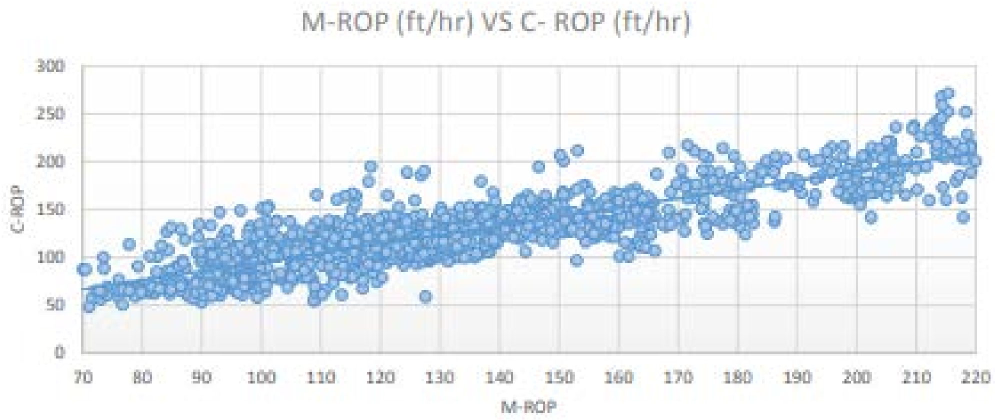


Figure 1. Calculated ROP vs actual ROP of depth and cross plot